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The AASERT supplement N00014-93-1-0824 provided partial support for three graduate students. The students performed research on an existing pure electron plasma containment apparatus, on a new laser-diagnosed ion plasma apparatus, and on a new camera-diagnosed electron apparatus. The transport experiments recently demonstrated that energy and particle transfer across magnetic fields can be greatly enhanced due to long-range interparticle collisions, stimulating new theory work. The experiments on collective plasma flows relate directly to conventional fluids, and demonstrated the spontaneous formation of "vortex crystal" states during the relaxation of 2D turbulence. These experiments are also relevant to the technologies of ion cluster traps used for spectroscopic studies (EBIT) and time standards (Penning Traps).

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The Department of Defense (DOD) requires certain information to evaluate the effectiveness of the AASERT program. By accepting this Grant Modification, which bestows the AASERT funds, the Grantee agrees to provide the information requested below to the Government's technical point of contact by each annual anniversary of the AASERT award date.

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C F Driscoll
Principal Investigator

28 Jun 96
Date

University of California, San Diego
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Final Technical Report

"Transport in Nonneutral Plasmas"

AASERT Grant N00014-93-1-0824

Office of Naval Research

1 Jun 93 - 31 May 96

Principal Investigator:

Prof. C. F. Driscoll

Students Supported:

Ms. A. C. Cass
Mr. E. M. Hollmann
Mr. J. M. Kriesel

Abstract

The AASERT supplement N00014-93-1-0824 provided partial support for three graduate students. The students performed research on an existing pure electron plasma containment apparatus, on a new laser-diagnosed ion plasma apparatus, and on a new camera-diagnosed electron apparatus. The transport experiments recently demonstrated that energy and particle transfer across magnetic fields can be greatly enhanced due to long-range interparticle collisions, stimulating new theory work. The experiments on collective plasma flows relate directly to conventional fluids, and demonstrated the spontaneous formation of "vortex crystal" states during the relaxation of 2D turbulence. These experiments are also relevant to the technologies of ion cluster traps used for spectroscopic studies (EBIT) and time standards (Penning Traps). A list of publications is attached.

For the last 14 years the plasma group at UCSD has been conducting an experimental and theoretical program of research on Pure Electron Plasmas Near Thermal Equilibrium, supported by the Office of Naval Research under contracts ONR N00014-82-K-0621 and N00014-89-J-1714. The program is scientifically well-staffed and well-equipped, but recent funding for this program did not include support for graduate students.

The AASERT supplement N00014-93-1-0824 provided partial support for three graduate students, who have contributed to and benefitted from the ONR-sponsored program. Total funding was 6 student-years. The students performed research on an existing pure electron plasma containment apparatus, and on a new laser-diagnosed ion plasma apparatus, and on a new camera-diagnosed electron apparatus. The attached list of publications were the primary means of disseminating the results of this research.

Plasma processes studied included energy and particle transfer across magnetic fields due to interparticle collisions, and due to collective fluid processes. The experiments on collisions, in close connection with theory, are establishing that long-range collisions can greatly enhance the transport of particles and energy across the magnetic field. The experiments on collective flows relate directly to conventional fluids, because these magnetized nonneutral plasmas are excellent laboratory manifestations of inviscid fluids in 2-dimensions. One of the most striking fluids observations was the spontaneous formation of organized "vortex crystal" states during the relaxation of 2D turbulence.

Experimental techniques and understandings developed for these bulk nonneutral plasmas are also directly applicable to the technologies of ion cluster traps used for

spectroscopic studies (EBIT), time standards (Penning Traps), and anti-matter containment. Additionally, the experimental apparatuses offered excellent training in the technologies of ultra-high-vacuum, cryopumping, super-conducting magnets, high-power pump and dye lasers, and harmonic generation. The students were supervised by Prof. Driscoll, with the collaboration of Prof. Tom O'Neil and Prof. Dan Dubin on theory problems.

The experimental research of Ms. Ann Cass on the new "CamV" apparatus has focused on 2D fluid processes, namely the free relaxation of turbulent flow and the damping of surface waves on a vortex patch. This is part of a broad program of "fluid" plasma transport, i.e. transport driven by flows, instabilities and nonlinear vortex dynamics. The new camera-based apparatus was built to allow high resolution imaging of these flows.

In general, hollow density plasmas may have a substantial shear in their drift rotation profiles and therefore exhibit the "diocotron" instability, which is the plasma analogue of the Kelvin-Helmholtz fluid instability. The instability undergoes nonlinear saturation with the formation of vortices, then the vortices decay into turbulent noise, and finally the noise decays leaving a reasonably quiet quasi-equilibrium. The plasma flow is mathematically identical to the convection of two-dimensional inviscid fluids, and we have pursued this scientific connection.

Two-dimensional turbulence normally relaxes through vortex merger and filamentation, with energy flowing to large scales and enstrophy dissipated on fine scales. We found that this relaxation can be arrested by the formation of vortex crystals. For some intial conditions, the chaotic motion of the vortices is "cooled," no further merger events occur, and the vortices form a rigidly rotating lattice within a uniform background of vorticity. We speculate that this cooling is caused by an interchange of energy between the motion of individual vortices and the background vorticity in which the vortices excite surface waves on the background.

Recently, we have been investigating the damping of these surface or "diocotron" waves in a well-controlled plasma. 2D fluid theory predicts that when the wave rotates at the same frequency as a fluid layer, damping will generate filamentary "cat's eyes," trapping this resonant fluid and limiting the wave damping. This nonlinear saturation of the damping is important in any real-world wave-fluid interactions, and the CamV apparatus is well-suited to imaging this nonlinear process.

The experimental research of Mr. Eric Hollmann has been conducted on the new laser-diagnosed ion apparatus. The apparatus contains magnesium ions in a 4 Tesla magnetic field. The Mg^+ ions are diagnosed through laser-induced fluorescence (LIF), using a 20 W ion-argon laser pumping a CW frequency-doubled ring dye laser operating in the ultraviolet at

280 nm at a power of about 2 mW.

The ion apparatus has enabled the measurement of *in situ* density profiles and velocity distributions, as well as the motion of test particles. The optical measurements are non-destructive, so measurements as a function of time give the cross-field particle flux directly. Flux measurements of test particle transport have shown that long-range collisions, which are ignored in classical plasma transport theory, can play an important role in plasma transport. The theory of these long-range interactions is presently being developed.

Additionally, direct LIF measurements of the parallel and perpendicular velocity distributions have been used to obtain thermal relaxation rates. The measured rates are in close agreement with classical theory, essentially "calibrating" the device and demonstrating that long-range collisions do not contribute to thermalization.

The transport from externally applied electric field asymmetries has also been studied. In particular, it has been demonstrated that a field asymmetry rotating faster than the plasma causes inward transport, and can be used to achieve steady-state confinement for up to two weeks. For typical operating conditions, this inward transport appears to be due to ions which have a resonance between their axial bounce and azimuthal drift rotation. We believe this "rotating wall" confinement technique will have wide applicability in charged particle confinement devices.

This new ion apparatus has offered excellent graduate student training in both plasma physics and in lasers. The plasma experiments have proven to be incisive as to the transport mechanisms at work. The laser diagnostic itself is a very sophisticated instrument and has enabled the student to learn about the operation of high-power ion-Argon lasers, dye lasers, and second harmonic generation cavities.

The experimental research of Mr. Jason Kriesel has been performed on the "EV" electron plasma apparatus, and closely complements the ion experiments. This apparatus is optimized for measuring the evolution of the radial density and temperature profiles of electron plasmas which are confined for very long times at low magnetic fields. Measurement of the density profile allows us to calculate the particle flux and the plasma $\mathbf{E}\times\mathbf{B}$ and diamagnetic drift rotation profiles. We find that the flux appears "viscous," in that it is proportional to the shear in the total rotation rate; but that the viscosity coefficient is larger and scales differently with magnetic field than predicted by classical theory. Again, these measurements directly relate to new theories of long-range "$\mathbf{E}\times\mathbf{B}$ drift" collisions which are presently being developed under ONR and NSF support.

A separate series of experiments on the EV apparatus has clarified the mechanism by which the initial plasmas are generated from the hot tungsten filament. In the regime where

the plasma formation depends on space-charge effects rather than on filament emission, an exact mathematical description of the plasma radial profile has been formulated. Experiments show that this description describes the experiments over a wide range of source parameters. The theory also predicts an absolute limit on the central plasma density, and shows that nonuniformities in the cathode emission are important in determing the plasma profile.

List of Publications

K.S. Fine, C.F. Driscoll and A.C. Cass, ''Observations of Vortex Crystals in 2D Turbulence,'' *Bull. Am. Phys. Soc.* **39**, 1736 (1994).

A.C. Cass, B. Cluggish, F. Anderegg, K.S. Fine, C.F. Driscoll and E. Sarid, ''Confinement Time Scalings of Non-neutral Plasmas,'' *Bull. Am. Phys. Soc.* **39**, 1737 (1994).

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J.B. Kadtke, K.S. Fine, C.F. Driscoll and A.C. Cass, ''Observing Hamiltonian Point Vortex Dynamics in a Confined Non-neutral Plasma,'' *Bull. Am. Phys. Soc.* **39**, 1921 (1994).

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A.C. Cass, K.S. Fine, and C.F. Driscoll, ''Inviscid Damping of Vortex Distortions,'' *Bull. Am. Phys. Soc.* **40**, 1977 (1995).

K.S. Fine, A.C. Cass and C.F. Driscoll, ''Observations of Vortex Crystals in 2D

Turbulence,'' *Bull. Am. Phys. Soc.* **40**, 2045 (1995).

K.S. Fine, C.F. Driscoll, A.C. Cass, T.B. Mitchell and X.-P. Huang, ''Instabilities, Turbulence and Organized Structures in Magnetized Electron Columns,'' to appear in Proc. of Crossed-Field Devices Workshop (Univ. of Michigan) -- 1996.

J.M. Kriesel and C.F. Driscoll, ''Electron Column from a Cathode with Radially Varying Potential,'' in preparation.